Luminous Compact Blue Galaxies up to $z \sim 1$ in the HST Ultra Deep Field: I. Small galaxies, or blue centers of massive disks?

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ABSTRACT

We analyze 26 Luminous Compact Blue Galaxies (LCBGs) in the HST/ACS Ultra Deep Field (UDF) at $z \sim 0.2-1.3$, to determine whether these are truly small galaxies, or rather bright central starbursts within existing or forming large disk galaxies. Surface brightness profiles from UDF images reach fainter than rest-frame $26.5\,B\,\mathrm{mag}/\square''$ even for compact objects at $z \sim 1$. Most LCBGs show a smaller, brighter component that is likely star-forming, and an extended, roughly exponential component with colors suggesting stellar ages $\gtrsim 100\,\mathrm{Myr}$ to few Gyr. Scale lengths of the extended components are mostly $\lesssim 2\,\mathrm{kpc}$, $> 1.5-2$ times smaller than those of nearby large disk galaxies like the Milky Way. Larger, very low surface brightness disks can be excluded down to faint rest-frame surface brightnesses ($\gtrsim 26\,B\,\mathrm{mag}/\square''$). However, 1 or 2 of the LCBGs are large, disk-like galaxies that meet LCBG selection criteria due to a bright central nucleus, possibly a forming bulge. These results indicate that $\gtrsim 90\%$ of high-z LCBGs are small galaxies that will evolve into small disk galaxies, and low mass spheroidal or irregular galaxies in the local Universe, assuming passive evolution and no significant disk growth. The data do not reveal signs of disk formation around

small, HII-galaxy-like LCBGs, and do not suggest a simple inside-out growth scenario for larger LCBGs with a disk-like morphology. Irregular blue emission in distant LCBGs is relatively extended, suggesting that nebular emission lines from star-forming regions sample a major fraction of an LCBG's velocity field.

Subject headings: galaxies: compact — galaxies: starburst — galaxies: structure — galaxies: evolution

1. Introduction

The term "Luminous Compact Blue Galaxies (LCBGs)" describes small, luminous ($\lesssim L_{\star,B}$), high-surface brightness galaxies with blue optical colors and strong emission lines (Guzmán et al. 2003; Garland et al. 2004; Werk et al. 2004). Such objects had previously been classified as e.g. Faint Blue Galaxies, Compact Narrow Emission Line Galaxies (CNELGs) (Koo et al. 1995; Guzmán et al. 1996), Luminous Compact Galaxies (Hammer et al. 2001, 2005), or Blue Compact Galaxies (Pisano et al. 2001), with varying selection criteria.

Prior work has indicated that LCBGs are progenitors of different intermediate - and low mass galaxies in the local Universe that are brightened by intense star formation (SF) (e.g. Koo et al. (1995), Guzmán et al. (1997)). Galaxies undergoing an LCBG phase may contribute $\sim 45\%$ of the comoving UV-derived SF rate density of the Universe and $\sim 20\%$ of the field galaxy number density at $z \sim 1$ (Phillips et al. 1997; Guzmán et al. 1997), and show the strongest known number density decline ($\times 10-100$) from intermediate z ($\sim 0.4-1$) to 0; they are almost absent in the local Universe (Koo et al. 1994; Guzmán et al. 1997; Phillips et al. 1997). LCBG phases do therefore contribute sizeably to the evolutionary phenomena observed in the whole galaxy population to $z = 1$ — the global increase of SF activity (Madau et al. 1996), and the luminosity and number density evolution of blue galaxies (Willmer et al. 2006; Faber et al. 2006).

This *letter* addresses the controversial question which types of local galaxies, or which of their subcomponents, experienced the LCBG phases of massive SF at redshifts $z \gtrsim 0.2$ to > 1. Koo et al. (1995), Guzmán et al. (1996, 1998) and Phillips et al. (1997) distinguished smaller LCBGs (half-light radius $r_e \lesssim 3\,\mathrm{kpc}$) with low velocity dispersion ($\sigma_v \lesssim 65\,\mathrm{km\,s^{-1}}$) and starburst dwarf–like morphologies, and larger, more massive LCBGs ($65 \lesssim \sigma_v \lesssim 160\,\mathrm{km\,s^{-1}}$), more similar to local irregular and starburst disk galaxies. They argued that the former may fade to ultimately become local low-mass spheroidals/dwarf ellipticals while the latter may evolve into local small disks and irregulars. On the other hand, Hammer et al. (2001, 2005) and Barton & van Zee (2001) suggested that LCBGs probably represent interaction-induced

formation of bulges in today's massive spiral galaxies, possibly accompanied by inside-out disk formation (Hammer et al. 2001). In this scenario, the apparently small linewidths and sizes of LCBGs do not represent intrinsic properties of these galaxies: as suggested by Koo et al. (1995) and shown by Barton & van Zee (2001), a nuclear starburst in an ordinary extended disk can skew its effective radius, effective surface brightness and colors to mimic a blue, compact galaxy. The nuclear burst's nebular emission would sample only the inner part of the galaxy's velocity field, and thus lead to an underestimate of its dynamical mass. This scenario becomes particularly worrisome with increasing redshift, where cosmological surface brightness dimming hampers the detection of low surface brightness (LSB) components, and nebular emission lines are usually the only indicator of faint galaxies' kinematics.

To constrain the above scenarios, we present the first structural study of the extended components in intermediate-z LCBGs, using the uniquely deep images from the HST/ACS Ultra Deep Field[1] (UDF) to search for extended disk components in 26 LCBGs. Details of this study can be found in an accompanying paper (Noeske et al. 2005c, in prep.; hereafter Paper II). Throughout this *letter*, we adopt a ΛCDM cosmology ($H_0 = 70\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.3, \Omega_\Lambda = 0.7$)

2. Sample selection and data processing

We adopted similar rest-frame selection criteria to those by Garland et al. (2004), Werk et al. (2004), Hoyos et al. (2004) for local LCBG samples: (i) blue rest-frame $B-V \leq 0.6$, (ii) average rest-frame surface brightness within the half-light radius $\mu_e \leq 21\,B\,\mathrm{mag}/\Box''$), (iii) $M_B \leq -18.5$, and (iv) half-light radius $r_e \leq 3.5\,\mathrm{kpc}$. These somewhat arbitrary limits include both extremely compact CNELGs, and larger LCBGs, more comparable to those analyzed by, e.g., Phillips et al. (1997). The galaxies were selected from the UDF SExtractor catalog (Beckwith et al., in prep.), after computing linear extents and rest-frame photometry, using the DEEP2 $k-$corrections (Willmer et al. 2006) and robust spectroscopic (Szokoly et al. 2004; Le Fèvre et al. 2004; Vanzella et al. 2005; Koo et al. 2005) and photometric redshifts (Wolf et al. 2004). After removing doubtful cases and 2 AGN, this yielded 26 objects at $0.21 < z < 1.25$, $\sim \frac{2}{3}$ at $z > 0.9$. See Fig. 1 for examples.

All LCBG images were analysed through two surface photometry methods: (i) 1-d surface brightness profiles (SBPs) were derived using the morphology-adaptive mask algorithm "LAZY" described in Papaderos et al. (2002) ("method iv") and Noeske et al. (2003), with

[1] 56, 56, 144 and 144 orbits of integration time in the B(F435W), V(F606V), i(F775W) and z(F850LP) filters respectively; PI: S. Beckwith, STScI

procedures detailed in these papers. LAZY can treat the irregular morphologies of LCBGs and is robust at low intensity levels, allowing to detect and measure, or reject, large LSB structures. The resulting SBPs typically showed approximately exponential, moderately extended components (see Section 3) which we fitted by exponential laws outside the brighter central excesses (see Noeske et al. (2003)). (ii) PSF effects on measured structural parameters of the extended components are non-negligible. For brighter components with roughly elliptical isophotes, PSF treatment is provided by the GALFIT code (Peng et al. 2002). We decomposed the LCBGs into two exponential components. Obviously unphysical fits due to very irregular morphologies were rejected, as well as fitted extended components fainter than an empirical reliability limit of 25 AB mag in i and z .

Comparisons between between LAZY and GALFIT, and reliability assessments are detailed in Paper II. Exponential scale lengths (R_s) from LAZY are typically overestimated for small objects ($R_s \lesssim 1.5\,\mathrm{kpc}$) by a factor of $\lesssim$1.3, few up to ~ 2, while for larger scale lengths, GALFIT can underestimate R_s by a factor $\lesssim 1.3$ (see Fig. 2). Both methods hence bracket the true scale lengths. Examples of SBPs are shown in Fig. 1. In most cases, the rest-frame B band SBPs reached beyond the rest-frame Holmberg radius ($26.5\,B\,\mathrm{mag}/\Box''$) even for compact objects at $z \sim 1$ (see object UDF0901 in Fig. 1).

3. Results

3.1. LCBGs: star formation within more extended, evolved galaxies

The SBPs of most LCBGs display a moderately extended, roughly exponential component, corresponding to a mostly fairly regular outer component in the images (Fig. 1). At smaller radii, the SBPs show brighter, smaller components, in excess of the extended exponentials. These range from bright nuclei to extended emission over a large part of the galaxy, and reflect the irregular blue emission seen in the images, i.e. probably the ongoing SF. For larger LCBGs, this structure has previously been reported (Koo et al. 1995; Phillips et al. 1997; Guzmán et al. 1998; Hammer et al. 2001). For smaller LCBGs, our current UDF dataset verifies what the data by Guzmán et al. (1998) suggested: also these objects, similar to local HII galaxies or distant CNELGs, have roughly exponential stellar components that pre-date the ongoing SF.

Rest-frame colors of the extended components are $-0.3 \lesssim U-B \lesssim 0.3$ and $0.3 \lesssim B-V \lesssim 0.9$ for $\sim 90\%$ of the LCBGs, on average ~ 0.2 mag redder than the SF excesses. For these colors, simple stellar population models for up to solar metallicity (Anders & Fritze - v.Alvensleben 2003) yield minimum stellar ages of $\gtrsim 100\,\mathrm{Myr}$ to several Gyr. More

extended SF histories (e.g. Bicker et al. (2004)) lead to higher ages. If extinction is significant in the extended components, outside strong SF, these age limits will decrease.

We will refer to 'extended components' rather than 'disks' as we lack resolved kinematic data for most objects. Morphologies are often disk-like for larger LCBGs (see 1), but ambiguous for small objects which could be either spheroids or disks.

3.2. Structure of the extended components

Figure 2 compares the extended components of the LCBGs to samples of nearby disk galaxies and dwarf galaxies with exponential SBPs. The disk sample by Lu (1998) was chosen because of its completeness of local field disk scalelengths, and the UMa-cluster sample by Tully et al. (1996) was added to include disks from higher density environments.

It is evident that the extended components of almost all LCBGs have small scale lengths ($R_s \lesssim 2\,\mathrm{kpc}$): at any given luminosity, they are comparable to the local disk galaxies with the smallest R_s. This result is robust against uncertainties of R_s. The less luminous exponential components are also compatible with those of relatively compact, luminous local dwarf galaxies (compact dEs, or stellar hosts of BCDs). The only two exceptions are UDF0900 (the LCBG with the largest R_s in Fig. 2, see also Fig. 1), which shows a large LSB component ($\mu_{0,B} \approx 22.9\mathrm{mag}/\Box''$, $R_s = 4.4\,\mathrm{kpc}$) with an exponential SBP but no spiral features, and a galaxy that may have a truncated disk with a small outer, but larger inner scalelength (Fig. 2)[2] Both galaxies have bright central regions that led to their classification as LCBGs.

4. Discussion and Conclusions

This structural study of their extended components reveals that $\sim 90\%$ of LCBGs at $z \sim 0.2-1.3$ are truly small galaxies. For these, suspected large disks with R_s similar to the MW, or the extended low-surface brightness component found in a local LCBG (NGC 7673), can be ruled out down to surface brightnesses $\gtrsim 26\,B\,\mathrm{mag}/\Box''$ (cf. Fig. 1). The discovery of 1, possibly 2 LCBGs ($\lesssim 10\%$) that are large, disk-like galaxies with bright nuclei supports the scenario of some LCBGs at higher z being nuclear starbursts, possibly bulge formation, in large disks.

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[2]The second-largest LAZY-derived scalelength in Fig. 2 is affected by PSF wings from a bright nucleus and in fact smaller; see the connected GALFIT data point.

The available scale lengths help to constrain the passive, post-starburst evolution scenario for LCBGs. Fading of the smaller, brighter SF component will affect the *overall* photometric structure of an LCBG. The older extended components alone will however likely fade more homogeneously and thus largely maintain their scale lengths. The extended components could fade by several mag, the bluest in principle up to 5 B mag from $z = 1$ to 0 if they were ∼100 Myr old simple stellar populations (see above). However, the scale lengths suggest that LCBGs evolve into local small disks, and different types of larger dwarf and low mass galaxies, assuming that their subsequent evolution does not involve strong disk growth[3].

Subsequent evolution into local large disks of at least the MW scale length would require an LCBG's extended stellar component to grow substantially, by a factor $\gtrsim 1.5$, typically > 2. The data cannot exclude, but neither evidence, such ongoing growth: For larger LCBGs with a disk-like morphology, we find no evidence of a simple inside-out growth such as bluening at large radii. For these galaxies, local disks with small scalelengths provide a possible descendant population, so that the substantial disk growth that Hammer et al. (2001, 2005) propose for similar and somewhat larger LCBGs may not be required[4]. From their linewidths, sizes, and stellar masses (Guzmán et al. (2003)), disk-like LCBGs could well be LCBG phases of local intermediate-mass ($M_\star \sim 10^{10} M_\odot$) disk galaxies, in agreement with the finding that such galaxies experienced substantial SF since $z \sim 1$ (Heavens et al. 2004; Bell et al. 2005; Hammer et al. 2005). Around small, HII-galaxy like LCBGs, we do not find signs of forming or pre-existing big disks. Their morphologies and sizes make these galaxies candidate progenitors of small, low mass galaxies in the local Universe, such as low mass spheroidals or irregulars. Resolved kinematic data will be important to constrain such scenarios.

We finally note that the blue, irregular emission in most LCBGs that are not large disks extends out to $\gtrsim 1.5$ to 2 scale lengths of the extended component (grey insets in Fig. 1). This fractional extent is similar to nearby LCBGs (Papaderos et al. 1996), where this blue emission is the locus of the ongoing SF and nebular emission. It appears plausible that irregular emission traces nebular emission also in distant LCBGs. If so, then nebular emission will sample a sufficient fraction of their velocity field to provide valid mass estimates: Pisano et al. (2001) showed that nebular emission line kinematics in nearby LCBGs trace neutral gas kinematics with moderate correction factors (~ 0.7). This lends support to distant LCBGs

[3]For low-mass LCBGs similar to Blue Compact Dwarf galaxies, also energy input from strong SF could affect their stellar mass distribution (Papaderos et al. 1996).

[4]Note that the selection criteria by Hammer et al. and this work are not fully comparable; their LCBG criteria may favor progenitors of larger local galaxies than our sample.

being mostly low- to intermediate mass galaxies.

In summary, most LCBGs at intermediate z show brighter, irregular, likely star-forming emission within more extended, regular components with approximately exponential intensity distributions and minimum stellar ages $\gtrsim$ 100 Myr. Most extended components have scale lengths by factors $> 1.5 - 2$ smaller than local large disks such as the Milky Way, while 1 or 2 of 26 LCBGs are larger, disk-like galaxies with bright nuclei. This suggests that $\sim$ 90% of LCBGs are progenitors of small disks, irregulars or low-mass spheroidals in the local Universe; $\sim$ 10% may represent bulge formation within massive disks.

We wish to thank Dr. M. Bershady for the WIYN R-band image of NGC7673. Research by DCK and KGN was partly funded by the NSF grant AST-0071198 and the HST grants GO-09126.02-A and AR-10321.02-A . We thank the referees for their valuable comments on this paper, and Dr. B. Holden for helpful advice on ACS PSF peculiarities.

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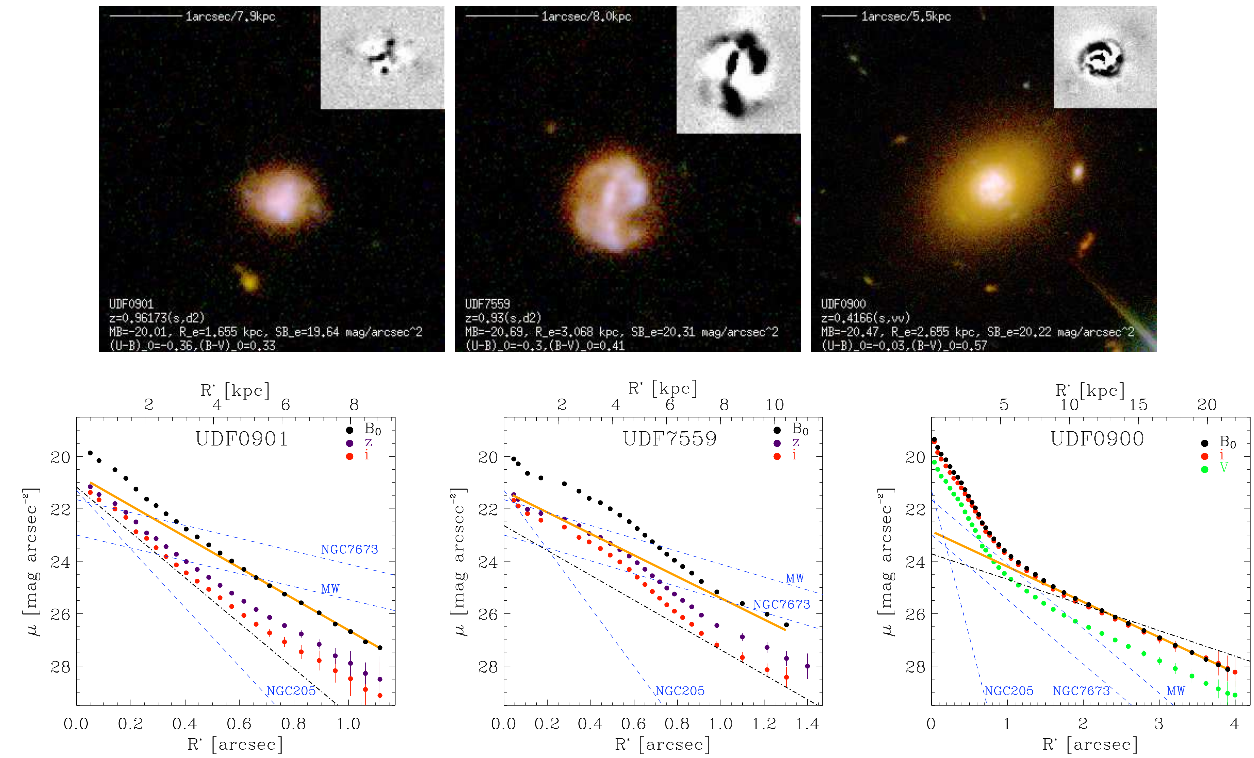

Fig. 1.— **Three-color images:** from HST B, V, i images, using non-linear, non-saturating intensity scaling (Lupton et al. 2004). UDF0901 (σ_v = 51.6 km/s) and UDF7559 (σ_v = 109.5 km/s) are examples for typical LCBGs- compact, narrow emission line (CNELGs) and more extended, broader-line objects. UDF0900 is one of two extended, low-surface brightness (LSB) galaxies with a bright, compact nucleus. **Gray insets:** small-scale i band residuals after subtracting smooth GALFIT models. Spatial scaling is equal to the three-color images. **Surface brightness profiles:** Colored dots (V, i, z) show the observed profiles closest in wavelength to the rest-frame B band. Black dots (B_0) denote the rest-frame $B_{\rm Vega}$ profile, k-corrected and corrected for cosmological surface brightness dimming. **Dashed blue lines:** The Milky Way (MW) disk, a LSB disk in a nearby LCBG (NGC 7673), and the dE NGC 205 (Choi et al. 2002) in rest-frame B, for comparison. Note the surface brightness limits of the rest-frame B SBPs > 26mag/$\square''$, and the detectability of large disks at redshifts $z \sim 1$. **Thick orange lines** show fits to the extended exponential components in rest-frame B LAZY profiles. **Dot-dashed lines** give the extended exponential component yielded by GALFIT decompositions in the i band, to illustrate PSF effects on LAZY-derived profiles.

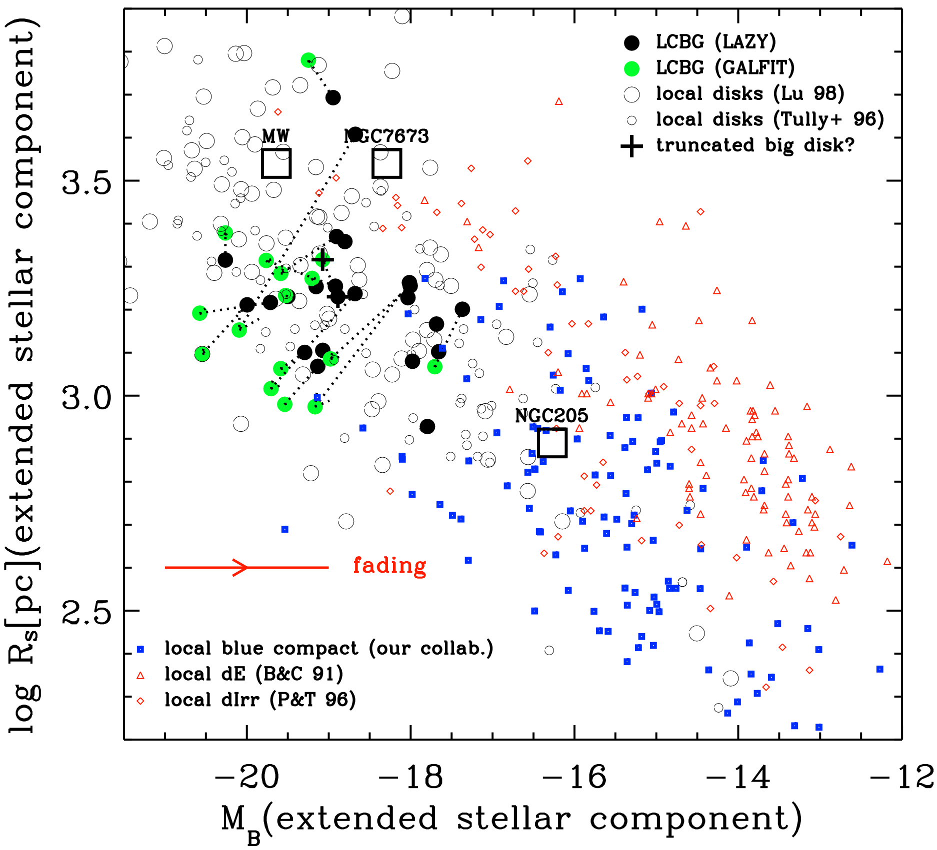

Fig. 2.— Exponential scale length R_s vs. absolute B band magnitude for the extended exponential components in LCBGs. Black filled circles denote LAZY, green ones GALFIT decompositions (see Section 2). LAZY scalelengths are inclination-corrected, assuming that the extended components are inclined disks, i.e. are upper limits for spheroids. Open circles: local disk galaxy samples from the UMa cluster (Tully et al. 1996) and from field environments in the local supercluster (Lu 1998). Blue squares: stellar host galaxies of Blue Compact Dwarfs (Gil de Paz & Madore (2005) and references therein), red lozenges: dwarf irregulars (Patterson & Thuan 1996), red triangles: dwarf ellipticals (Binggeli & Cameron 1991). Open boxes: the dwarf elliptical NGC 205 Choi et al. (2002), and the disks of the MW (3.5 kpc, de Vaucouleurs & Pence (1978)) and the the nearby LCBG candidate NGC7673 (see Pisano et al. (2001); SBP derived in this work, see Paper II). The arrow shows the effect of fading.